Impedance Issues in SSI of Embedded and Deeply Embedded Structures

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Outline

- Impedance of deeply embedded structures
- Soil box impedance
- Effect of varying wave fields

Note:
- This talk represents a snapshot of work in progress.
- Mixed results:
  - Some good
  - Some less than acceptable
- Sharing is encouraged
Embedded Cylinder Impedance

- Rigid massless cylinder
- Embedment=2\cdot\text{radius}
- Symmetry
- Direct solution
- Different meshes

\[ f \leq \frac{V_s}{6h} \quad f \leq \frac{V_s}{10h} \]
Horizontal Impedance

- Poor comparison for $a_o > 3$
- Minor improvement with mesh refinement
- At $a_o = 3$, the fine mesh has $V_s/21h$
- Something besides mesh issues are perturbing the solution
Vertical Impedance

- Poor comparison for $a_o > 2.5$
- Minor improvement with mesh refinement
- Something besides mesh issues are perturbing the solution
Embedded Cylinder Impedance

- Same problem, with an embedment of 0.5•radius
- $V_s/6h$ model
Summary of 
Deeply Embedded Structures

- SASSI V&V project considered embedment depths up to 50% of the effective radius
- Preliminary results for deeper embedment are unsatisfactory
  - Additional work is required to understand existing results and path forward
- Engineers are cautioned to ensure that their V&V fully encompasses the full range of parameters being evaluated
Soil Box Impedance

- Considering implementing time domain SSI
  - Can we implement, execute and defend analyses?
- Proposed models
  - Structure
  - Boundary
  - Soil box
Soil Box Impedance

• Linear frequency domain SSI experience
  – Extensive V&V of soil impedance
    • What works
    • What doesn't work

• How does the time domain soil impedance compare with frequency domain benchmarks?
Impedance Comparison Methodology

• Focus on boundaries and soil box size
  – Omit nonlinear soil models
• Use common damping formulation
  – Abaqus viscoelastic soil model can be equal to SASSI complex soil damping
• Limited to lumped mass matrix
• Initial comparisons in frequency domain
  – Abaqus steady state dynamics with direct option yields complex stiffness and displacement
  – Use transmitting boundary (infinite elements) to calibrate soil box size
  – Rerun with alternate boundaries
• Time domain comparison
  – Abaqus explicit
• Exploratory
  – Quick runs
• Frequency domain
• Calibrate damping
• Transmitting boundary
  – Limited to symmetric load
  – Asymmetric infinite boundary would be helpful
• SASSI V&V Task 6 Problem 5
  – Model parameters
    • \( r \) = foundation radius
    • \( a \) = soil box radius
Axisymmetric Modeling

- High frequency behavior is good
  - Mesh $\approx V_s/(10f_{\text{max}})$
  - Initial mesh was problematic
- Low frequency behavior is problematic
  - Wavelength, $\lambda \approx 0.9V_s/f \approx 5.6r/a_o$
    - $a=2r \rightarrow \lambda=a$ at $a_o=2.8$
    - $A=6r \rightarrow \lambda=a$ at $a_o=0.9$
  - Response degrades when soil box radius, $a \leq \lambda$
    - Mesh with infinite elements
    - Preliminary results
3D Modeling

- **Quarter symmetry**
  - Some frequency domain runs are slow

- **SASSI V&V Task 8 Problem 1**
  - Square rigid massless surface plate, half-width=a
  - Uniform half-space

- **Cases:**
  - Infinite boundary
  - Side constraint plus infinite boundary on base only
3D Modeling – Frequency Domain

- Horizontal unit load
- Investigate soil box size
  - Low frequency problems similar to axisymmetric case
  - Response degrades when soil box width, \( L \leq \lambda \)
    - \( L=2a \rightarrow \lambda=L \) at \( a_o=2.8 \)
    - \( L=8a \rightarrow \lambda=L \) at \( a_o=0.7 \)
3D Modeling – Frequency Domain

- Horizontal unit load
- Compare soil box mesh density
  - \( L=8a \) for all meshes
  - Each mesh meets \( \lambda/5 \)
  - Response degrades at frequencies > \( \lambda/10 \)
  - Note: Response is based on lumped mass matrix
3D Modeling – Frequency Domain

- Horizontal unit load
- Compare transmitting and restrained boundaries
  - $L = 8a$
  - Each mesh meets $\lambda/5$
  - Restrained boundary has spurious response due to reflected energy
Time Domain Response

- Abaqus explicit
- Response to unit impulse
- Significant reflections in constrained boundary solution

To do...
- Refine data extraction
- Understand high frequency noise in horizontal response
- Extract frequency domain displacement TF and compare to benchmark
Summary of Soil Box Impedance Study

- **Preliminary results**
  - Work in progress

- **Abaqus transmitting boundary**
  - Good comparisons with benchmark
  - 6-node wedge would be very useful

- **Side constraint plus infinite boundary on base only**
  - Reflections from side constraint corrupt solution at L=8a

- **Mesh requirements**
  - High frequency: element size < Vs/10h
  - Low frequency: soil box size > \( \lambda \)

- **Overall, promising results**
  - Additional work needed before implementation on a safety basis project
Effect of Varying Wave Fields on SSI Loads

● Current practice
  – Analyze vertically propagating P and S-waves
    • Maximize response in a surface or shallowly embedded structure
  – Magnitude anchored to input spectra at some elevation

● Actual wave field
  – Combined body and surface waves
    • P-wave, S-wave
    • Rayleigh wave, Love wave

● Potential issues
  – Are P and S wave fields realistic for both shallow and deeply embedded structures?
  – How do we evaluate alternate wave fields?
  – Does the actual wave field impact response?
P and S Wave Fields

$V_p \approx 2000$ fps  
$\lambda_P = 400$ ft @ 5hz

$V_s = 1000$ fps  
$\lambda_S = 200$ ft @ 5hz

- Embedment, $e=100'$, Radius, $r=50'$, $e/r=2$
- Control point at surface
- Seismic input averaged over the depth of embedment is much less than a surface foundation.
Evaluation of Alternate Wave Field

• Wave field generation
  – Active R&D
  – Current study uses PUNCH to generate plane strain waves

• Analysis
  – Seismic load vector \( F = K \Delta \)
  – Use PUNCH to develop free field displacement, \( \Delta \)
  – Use SASSI for soil impedance, \( K \)
  – Import frequency dependent load vector into SASSI
  – Solve using traditional frequency domain approach
Wave field generation

Layer 1: \( V_s = 1000 \text{ fps} \); 
Dens. = 110 pcf; \( \nu = 0.3 \)
h = 200 ft

Halfspace: \( V_s = 4000 \text{ fps} \); 
Dens. = 110 pcf; \( \nu = 0.25 \)

Layer 2: \( V_s = 2000 \text{ fps} \); 
Dens. = 110 pcf; \( \nu = 0.25 \)
h = 100 ft

Unit amplitude source

100 ft

Receivers
10 wide by 10 deep; 10’ grid

150 ft

Figure 3-16. Distribution of displacement waves from a circular footing on a homogeneous, isotropic, elastic half-space (from Woods, 1968).
5 Hz Wave From Vertical Surface Input

- Primarily Rayleigh wave
  - $\lambda_R \approx 180'$
  - $\lambda_R/2 \approx$ building width
  - Input is down on left size, up on right side with coupled translation
  - Direction and amplitude of input changes with phase angle
2 and 20 Hz Excitation

Loads in phase, greater total load than traditional analysis assumptions

Out of phase loading can have a significant impact on structural response.

Loads out of phase, smaller total load than traditional analysis assumptions

2 Hz, width≈λ_R/5

20 Hz, width≈2λ_R
Effect of Wave Fields

- Vertically propagating P-Wave
  - Analytical idealization
    - Yields spurious results in 1D convolution analyses
    - PSHA & Site studies use empirical V/H ratios

- Surface Waves
  - Combined vertical and horizontal input
  - Coherent building input when \( \lambda_R > \) building width
    - More total load for deeply embedded structures
  - Incoherent building input when \( \lambda_R < \) building width
    - Less total load for all structures at high frequencies
    - Excite building responses not observed in traditional analyses.
Summary for Varying Wave Fields on SSI Loads

- Surface waves are a viable alternative to traditional seismic input
  - Provide better insight into actual seismic response
    - Coherent low frequency input
    - Incoherent high frequency input
  - Superposition of multiple waves could be used to develop ground motions meeting target spectra
    - Additional work required to develop design motion
- Surface waves can be evaluated using existing analysis tools